

# Sampling complete designs

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## Abstract

Suppose  $\Gamma'$  to be of a subgraph of a graph  $\Gamma$ . We define a *sampling* of a  $\Gamma$ -design  $\mathfrak{B} = (V, B)$  into a  $\Gamma'$ -design  $\mathfrak{B}' = (V, B')$  as a surjective map  $\xi : B \rightarrow B'$  mapping any block of  $B$  into one of its subgraphs. A sampling will be called *regular* when the number of preimages of any block of  $B'$  under  $\xi$  is a constant. This new concept is closely related with the classical notion of *embedding*, which has been extensively studied, for many classes of graphs, by several authors; see, for example, the survey [28]. Actually, a sampling  $\xi$  might induce several embeddings of the design  $\mathfrak{B}'$  into  $\mathfrak{B}$ , although the converse is not true in general. In the present paper we study in more detail the behaviour of samplings of  $\Gamma$ -complete designs of order  $n$  into  $\Gamma'$ -complete designs of the same order and show how the natural necessary condition for the existence of a regular sampling is actually sufficient. We also provide some explicit constructions of samplings, as well as propose further generalizations.

**Keywords:** sampling; embedding, (complete) design.

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## 1 Introduction

Denote by  $K_n$  the complete graph on  $n$  vertices, and assume  $\Gamma \leq K_n$  to be a subgraph of  $K_n$ . Write  ${}^\lambda K_n$  for the multigraph obtained from  $K_n$  by repeating each of its edges exactly  $\lambda$  times. A  $({}^\lambda K_n, \Gamma)$ -*design* is a set  $\mathfrak{B}$  of graphs, called *blocks*, isomorphic to  $\Gamma$  and partitioning the edges  ${}^\lambda K_n$ . Recall that an automorphism of  $\mathfrak{B}$  is a permutation of the vertices of  $K_n$  leaving  $\mathfrak{B}$  invariant. These designs, especially those with  $\lambda = 1$  and endowed with a rich automorphism group, are a topic of current research; several constructions, as well as existence results, are known; see, for instance, [2, 3, 27]. We generalize the classical concept of  $(v, k)$ -complete design, see [6, 23], to the context of graph decompositions.

**Definition 1.1.** Suppose  $\Gamma \leq K_n$ . By a  $(K_n, \Gamma)$ -*complete design* we mean the set  $K_n(\Gamma)$  consisting of all subgraphs of  $K_n$  isomorphic to  $\Gamma$ .

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Clearly, a  $(K_v, K_k)$ -complete design is just a  $(v, k)$ -complete design.

The main topic of this paper is the new concept of *sampling* of designs; we propose the following definition.

**Definition 1.2.** Given a  $({}^\lambda K_n, \Gamma)$ -design  $\mathfrak{B}$  and a  $({}^\mu K_v, \Gamma')$ -design  $\mathfrak{B}'$  with  $\Gamma' \leq \Gamma$ , a  $\mathfrak{B}'$ -*sampling* of  $\mathfrak{B}$  is a surjective function  $\xi : \mathfrak{B} \rightarrow \mathfrak{B}'$  such that  $\xi(B) \leq B$ , for any  $B \in \mathfrak{B}$ .

When  $n = v$  and  $\lambda = \mu = 1$ , we shall speak simply of  $\Gamma'$ -samplings of  $\mathfrak{B}$ . In general, to prove the existence of samplings of arbitrary designs is an interesting yet difficult problem. In the present paper, we shall be concerned with samplings of complete designs.

Our notion of sampling is closely related to that of embedding of designs. We recall that an *embedding* of  $\mathfrak{B}'$  into  $\mathfrak{B}$ , see [28], is a function  $\psi : \mathfrak{B}' \rightarrow \mathfrak{B}$  such that for any  $G \in \mathfrak{B}'$ ,

$$G \leq \psi(G).$$

In recent years, embeddings have been extensively investigated and several results have been obtained for various classes of graphs; see for instance, [7, 10, 17, 21, 24, 25, 26, 29, 30]. An injective embedding is called *strict*. Note that given a sampling  $\xi : K_n(\Gamma) \rightarrow K_n(\Gamma')$ , there is always a strict embedding  $\psi : K_n(\Gamma') \rightarrow K_n(\Gamma)$  such that  $\xi\psi$  is the identity on  $K_n(\Gamma')$ . However, the reverse, namely that any strict embedding induces a sampling, is not true, unless the embedding is taken to be bijective.

Samplings are also related to nestings of cycle systems; see Section 2 for some details.

We also propose this new definition for samplings between complete designs.

**Definition 1.3.** A *regular*  $\Gamma'$ -*sampling* of the complete design  $K_n(\Gamma)$  is a sampling  $\xi : K_n(\Gamma) \rightarrow K_n(\Gamma')$  such that the number of preimages of any  $G \in K_n(\Gamma')$  is a constant  $\lambda > 0$ . Such a sampling is said to have *redundancy*  $\lambda$ .

Observe that constructing a regular  $\Gamma'$ -sampling of redundancy  $\lambda$  is the same as to extract from every block of  $K_n(\Gamma)$  a subgraph isomorphic to  $\Gamma'$  in such a way as to cover the set  $K_n(\Gamma')$  exactly  $\lambda$  times.

Analogously, we may generalize strict embeddings as follows.

**Definition 1.4.** A  $\lambda$ -*fold regular embedding* of  $K_n(\Gamma')$  in  $K_n(\Gamma)$  is an embedding  $\psi : K_n(\Gamma') \rightarrow K_n(\Gamma)$  such that any  $G \in K_n(\Gamma)$  has  $\lambda$  preimages under  $\psi$ .

Clearly, for an embedding, it is equivalent to be strict and to be 1-fold regular.

The main result of the present paper is contained in Theorem 4.3: it shows that the natural necessary conditions for the existence of regular  $\Gamma'$ -samplings and  $\lambda$ -fold regular embeddings for  $K_n(\Gamma)$  are also sufficient. Theorem 4.6 shows that when the hypotheses of Theorem 4.3 are not fulfilled, there might still exist, in some cases, samplings with some regularity.

In Section 5, we shall provide some direct constructions of regular samplings, using suitable automorphism groups, and focusing our attention to the case in which both  $\Gamma$  and  $\Gamma'$  are complete graphs. We will also propose a generalisation of the notion of  $(K_n, \Gamma)$ -complete design to arbitrary graphs.

## 2 Samplings and nestings

In this section we use standard notations of graph theory; see [14]. In particular, by  $C_m$  we mean the cycle of length  $m$ , whereas  $S_{m+1}$  denotes the star with  $m$  rays and  $m + 1$  vertices; with  $W_{m+1}$  we write the wheel with  $m + 1$  vertices, that is the graph obtained from a cycle  $C_m$ , by adding a further vertex adjacent to all the preexisting ones.

An  $m$ -cycle system  $\mathfrak{C}$  of order  $n$  is just a  $(K_n, C_m)$ -design; see [4]. A *nesting* of  $\mathfrak{C}$  is a function  $f : \mathfrak{C} \rightarrow V(K_n)$  such that

$$\mathfrak{S} = \{\{x, f(C)\} \mid C \in \mathfrak{C}, x \in V(C)\}$$

is a  $(K_n, S_{m+1})$ -design.

Nestings of cycle systems have been extensively studied; see [9, 11, 18, 19, 20, 31, 32]. Observe that, by construction, a nesting of  $\mathfrak{C}$  always determines a bijection  $g : \mathfrak{C} \rightarrow \mathfrak{S}$ . We may consider the set

$$\mathfrak{W} = \{C \cup g(C) \mid C \in \mathfrak{C}\}.$$

All elements of  $\mathfrak{W}$  are wheels  $W_{m+1}$ . It is immediate to see that  $\mathfrak{W}$  is a  $({}^2K_n, W_{m+1})$ -design. Since both  $C_m \leq W_{m+1}$  and  $S_m \leq W_{m+1}$ , there exists at least two samplings,  $\xi_1 : \mathfrak{W} \rightarrow \mathfrak{C}$  and  $\xi_2 : \mathfrak{W} \rightarrow \mathfrak{S}$ . Actually, it is possible to reconstruct the nesting from just  $\xi_2$ , as shown in the following proposition.

**Proposition 2.1.** *Suppose  $\mathfrak{W}$  to be a  $({}^2K_n, W_{m+1})$ -design and let  $\mathfrak{S}$  be a  $(K_n, S_m)$ -design. There exists a sampling  $\xi : \mathfrak{W} \rightarrow \mathfrak{S}$  if, and only if, there is a nesting of an  $m$ -cycle system  $\mathfrak{C}$  of order  $n$ .*

*Proof.* For any  $W \in \mathfrak{W}$ , let  $\zeta(W) = W \setminus \xi(W)$ . Clearly  $\zeta(W)$  is always an  $m$ -cycle. Since  $\mathfrak{W}$  is a  $({}^2K_n, W_{m+1})$ -design and  $\mathfrak{S}$  is a  $(K_n, S_m)$ -design, the set

$$\mathfrak{C} = \{\zeta(W) \mid W \in \mathfrak{W}\}$$

is an  $m$ -cycle system of order  $n$ . Define now  $f : \mathfrak{C} \rightarrow V(K_n)$  as the function which sends any cycle  $C = \zeta(W)$  into the centre of the wheel  $W$ . The function  $f$  is a nesting, as required.  $\square$

**Remark 2.2.** In the proof of Proposition 2.1, it is essential to have that  $\zeta(W) = W \setminus \xi(W)$  is a cycle  $C_m$ . In general, any wheel  $W_{m+1}$  contains  $m + 1$  cycles  $C_m$ . However, for  $m > 3$  only one of these cycles, say  $C$ , is such that  $W_{m+1} \setminus C$  is a star. Hence, a sampling  $\xi' : \mathfrak{W} \rightarrow \mathfrak{C}$ , is not, in general, associated with a sampling  $\mathfrak{W} \rightarrow \mathfrak{S}$ ; thus, we may not have a nesting.

## 3 Preliminaries on graph and matching theory

Here we recall some known results about matchings of bipartite graphs; for further references, see [22, 33].

By graph we shall always mean a finite unordered graph  $\Gamma = (V, E)$  without loops, having vertex set  $V$  and edge set  $E$ .

Recall that a graph  $\Gamma = (V, E)$  is *bipartite* if  $V$  can be partitioned into two sets  $\Gamma_1, \Gamma_2$  such that every edge of  $\Gamma$  has one vertex in  $\Gamma_1$  and one in  $\Gamma_2$ . The degree of  $v \in V$  in  $\Gamma$  is the number  $\deg_\Gamma(v)$  of edges of  $\Gamma$  containing  $v$ . A bipartite graph  $\Gamma = \Gamma_1 \cup \Gamma_2$  is  $(d, e)$ -*regular* if each vertex in  $\Gamma_1$  has degree  $d$  while each vertex in  $\Gamma_2$  has degree  $e$ . If  $d = e$ , we say that  $\Gamma$  is *regular of degree*  $d$ .

A *matching* in any graph  $\Gamma$  is a set of edges of  $\Gamma$ , no two of which are incident. A *perfect matching* (or *1-factor*) of  $\Gamma$  is a matching partitioning the vertex set  $V(\Gamma)$ . In a bipartite graph  $\Gamma = \Gamma_1 \cup \Gamma_2$ , a matching is *full* if it contains  $\min(|\Gamma_1|, |\Gamma_2|)$  edges. Clearly, a full matching of  $\Gamma$  is perfect if, and only if,  $|\Gamma_1| = |\Gamma_2|$ .

The following lemma shall be used throughout the paper.

**Lemma 3.1** ([1], pag. 397, Corollary 8.13). *Any bipartite  $(d, e)$ -regular graph  $\Gamma$  possesses a full matching.*

An *edge colouring* of  $\Gamma$  is a function  $w : E \rightarrow \mathbb{N}$  such that for any incident edges, say  $e_1, e_2$ ,

$$w(e_1) \neq w(e_2).$$

An  $n$ -*edge colouring* of  $\Gamma$  is an edge colouring using exactly  $n$  colours. The *chromatic index*  $\chi'(\Gamma)$  is the minimum  $n$  such that  $\Gamma$  has an  $n$ -edge colouring.

**Theorem 3.2** (König Line Colouring Theorem, [15, 16]). *For any bipartite graph  $\Gamma$ ,*

$$\chi'(\Gamma) = \max_{v \in \Gamma} \deg_\Gamma(v).$$

For a proof in English of this result and more references on the topics, see [22, Theorem 1.4.18] and the discussion therein.

## 4 Embeddings and samplings of $(K_n, \Gamma)$ -complete designs

Throughout this section, let  $\Gamma' \leq \Gamma$  be two subgraphs of  $K_n$ .

By  ${}^\lambda K_n(\Gamma)$  we will denote the multiset obtained from  $K_n(\Gamma)$  by repeating each of its elements exactly  $\lambda$  times.

**Lemma 4.1.** *Let  $b_1$  be the number of blocks of  $K_n(\Gamma)$  and  $b_2$  be that of  $K_n(\Gamma')$  and let  $m = \text{lcm}(b_1, b_2)$ . Then there is a bijective embedding*

$$\psi : {}^{(m/b_2)} K_n(\Gamma') \rightarrow {}^{(m/b_1)} K_n(\Gamma).$$

*Proof.* Introduce the bipartite graph  $\Delta = (V, E)$  where  $V = K_n(\Gamma) \cup K_n(\Gamma')$  and  $x, y \in V$  are adjacent if, and only if,  $x \neq y$  and either  $x \leq y$  or  $y \leq x$ .

In the first step of the proof, we verify that  $\Delta$  is  $(d, e)$ -regular, for some  $d, e \in \mathbb{N}$ . As the automorphism group of  $K_n$  is  $\text{Aut}(K_n) \simeq S_n$ , we have that

$\text{Aut}(K_n)$  is transitive on both  $K_n(\Gamma)$  and  $K_n(\Gamma')$ . We now argue by way of contradiction. Suppose that there are  $\Gamma_1, \Gamma_2 \in K_n(\Gamma)$  such that

$$d_1 = \deg \Gamma_1 < \deg \Gamma_2 = d_2.$$

Then, there exists  $\sigma \in \text{Aut}(K_n)$  such that  $\sigma(\Gamma_2) = \Gamma_1$ . In particular, the image under  $\sigma$  of the  $d_2$  subgraphs of  $\Gamma_2$  isomorphic to  $\Gamma'$  consists of  $d_2$  subgraphs of  $\Gamma_1$ , all isomorphic to  $\Gamma'$ . However, we supposed the number of subgraphs of  $\Gamma_1$  isomorphic to  $\Gamma'$  to be  $d_1 < d_2$ ; this yields a contradiction.

Likewise, suppose we have two graphs  $\Gamma'_1, \Gamma'_2 \in K_n(\Gamma')$  with

$$e_1 = \deg \Gamma'_1 < \deg \Gamma'_2 = e_2.$$

As  $\text{Aut}(K_n)$  is transitive on  $K_n(\Gamma')$ , there is  $\sigma \in \text{Aut}(K_n)$  with  $\sigma(\Gamma'_2) = \Gamma'_1$ . This permutation  $\sigma$ , in particular, sends the  $e_2$  graphs isomorphic to  $\Gamma$  containing  $\Gamma'_2$  into  $e_2$  distinct graphs containing  $\Gamma'_1$  isomorphic to  $\Gamma$ . This yields a contradiction, since  $e_1 < e_2$ .

Let now  $\Delta'$  be the graph obtained from  $\Delta$  by replicating  $(m/b_1)$ -times  $K_n(\Gamma)$  and  $(m/b_2)$ -times  $K_n(\Gamma')$ . By construction,  $\Delta'$  is a  $(dm/b_2, em/b_1)$ -regular bipartite graph. By Lemma 3.1,  $\Delta$  admits a full matching  $M$ . Furthermore, since both parts of  $\Delta$  have the same cardinality,  $M$  is perfect.

For any  $x \in K_n(\Gamma)$ , define  $\psi(x) = y$  where  $(x, y) \in M$ . This provides an embedding, as required.  $\square$

**Remark 4.2.** Since  $\psi$  in Lemma 4.1 is bijective, the function

$$\xi = \psi^{-1} : {}^{(m/b_1)}K_n(\Gamma) \rightarrow {}^{(m/b_2)}K_n(\Gamma')$$

is a sampling.

Now we are ready to prove our main result.

**Theorem 4.3.** *The complete design  $K_n(\Gamma)$  admits a regular  $\Gamma'$ -sampling if, and only if, there is  $\lambda \in \mathbb{N}$  such that*

$$|K_n(\Gamma)| = \lambda |K_n(\Gamma')|. \quad (1)$$

*The redundancy of any such sampling is  $\lambda$ .*

*Conversely, there is a  $\lambda$ -fold regular embedding of  $K_n(\Gamma')$  in  $K_n(\Gamma)$  if, and only if*

$$|K_n(\Gamma')| = \lambda |K_n(\Gamma)|.$$

*Proof.* Clearly, Condition (1) is necessary for the existence of a regular  $\Gamma'$ -sampling. By Remark 4.2, there is a bijective sampling

$$\vartheta : K_n(\Gamma) \rightarrow {}^\lambda K_n(\Gamma').$$

Each  $y \in K_n(\Gamma')$  appears exactly  $\lambda$  times in  ${}^\lambda K_n(\Gamma')$ . As such,  $y$  is the image of  $\lambda$  elements of  $K_n(\Gamma)$  under  $\vartheta$ . Thus,  $\vartheta$  induces a regular  $\Gamma'$ -sampling  $\xi : K_n(\Gamma) \rightarrow K_n(\Gamma')$  with redundancy  $\lambda$ .

The second part of the theorem is proved in an analogous way, using the bijective embedding

$$\psi : K_n(\Gamma') \rightarrow {}^\lambda K_n(\Gamma)$$

provided by Lemma 4.1.  $\square$

We have to point out that the proof of previous theorem is not constructive. In order to determine actual samplings we may, in general, to use some of the algorithms for matchings in graphs, like the ones in [22], applied to the graph  $\Delta'$  of Lemma 4.1. Also, in Section 5, we will construct explicitly regular samplings for some complete designs.

When  $|K_n(\Gamma')|$  is not a divisor of  $|K_n(\Gamma)|$ , the previous theorem fails. Under the assumption

$$|K_n(\Gamma)| = \lambda|K_n(\Gamma')| + r,$$

with  $0 < r < |K_n(\Gamma')|$ , we may investigate the existence of sampling functions which are “as regular as possible”, namely in which the number of preimages of any given element is either  $\lambda$  or  $\lambda + 1$ . These samplings shall be called  $(\lambda, \lambda + 1)$ -semiregular.

We start with the following lemma.

**Lemma 4.4.** *Suppose*

$$\lambda = \left\lfloor \frac{|K_n(\Gamma)|}{|K_n(\Gamma')|} \right\rfloor;$$

*then, there is a strict embedding  $\xi : {}^\lambda K_n(\Gamma') \rightarrow K_n(\Gamma)$ .*

*Proof.* Argue as in the first part of the proof of Lemma 4.1 and introduce the  $(d, e)$ -regular graph  $\Delta = (V, E)$ . Let now  $\Delta'$  be the graph obtained from  $\Delta$  by replicating  $\lambda$ -times  $K_n(\Gamma')$ . As  $\Delta'$  is a  $(\lambda d, e)$ -regular bipartite graph, it admits by Lemma 3.1 a full matching  $M$  of size  $\lambda|K_n(\Gamma')|$ ; in particular, each vertex in  ${}^\lambda K_n(\Gamma')$  is matched to exactly one vertex of  $K_n(\Gamma)$ .  $\square$

By collapsing the multiset  ${}^\lambda K_n(\Gamma')$  in the proof of the previous lemma, we have that  $M$  associates  $\lambda$  elements of  $K_n(\Gamma)$  to each element of  $K_n(\Gamma')$ . This leads to the following corollary.

**Corollary 4.5.** *Suppose*

$$\lambda = \left\lfloor \frac{|K_n(\Gamma)|}{|K_n(\Gamma')|} \right\rfloor;$$

*then, there exists a sampling  $\xi : K_n(\Gamma) \rightarrow K_n(\Gamma')$  such that any  $g \in K_n(\Gamma')$  has at least  $\lambda$  preimages.*

It can be seen directly from Corollary 4.5 that when

$$|K_n(\Gamma)| = \lambda|K_n(\Gamma')| + 1,$$

there always exists a  $(\lambda, \lambda + 1)$ -semiregular sampling. In general, however, further hypotheses on the nature of the embedding of  $K_n(\Gamma')$  into  $K_n(\Gamma)$  are required. We prove a result for the case  $\lambda = 1$ .

**Theorem 4.6.** *Let  $\Gamma' \leq \Gamma \leq K_n$  and let*

$$|K_n(\Gamma)| - |K_n(\Gamma')| = r < |K_n(\Gamma')|. \quad (2)$$

*Suppose*

$$|K_n(\Gamma)| > \frac{er^2}{e+r-1}, \quad (3)$$

*where  $e \in \mathbb{N}$  is the number of elements of  $K_n(\Gamma)$  containing  $\Gamma'$ . Then, there is a  $(1, 2)$ -semiregular sampling  $\xi : K_n(\Gamma) \rightarrow K_n(\Gamma')$ .*

*Proof.* Argue as in the proof of Lemma 4.1, and construct a  $(d, e)$ -regular bipartite graph  $\Delta$ . As

$$d|K_n(\Gamma)| = e|K_n(\Gamma')|, \quad (4)$$

by (2) we have

$$(e-d)|K_n(\Gamma')| = dr > 0.$$

Thus  $(e-1) \geq d$ . Also, by (2) and (4), we have  $er = (e-d)|K_n(\Gamma)|$ , hence using (3) it results

$$d > \frac{r-1}{r}(e-1).$$

Determine now, using Lemma 3.1, a full matching of  $\Delta$ ; this provides values for the function  $\xi$  on a subset  $T$  of  $K_n(\Gamma)$  with  $T = |K_n(\Gamma')|$ . Let now  $R = K_n(\Gamma) \setminus T$  be the set of the vertices of  $K_n(\Gamma)$  which have not been already matched, and consider the bipartite graph  $\Delta' = (V', E')$  obtained from  $\Delta$  by keeping just the vertices in  $R \cup K_n(\Gamma')$ . This graph, in general, is not regular; however,  $\deg_{\Delta'}(v) = d$  if  $v \in R$  and  $\deg_{\Delta'}(v) < e$  if  $v \in K_n(\Gamma')$ . By Theorem 3.2,  $\chi'(\Delta') \leq e-1$ . Let  $w : V' \rightarrow L \subset \mathbb{N}$  be a colouring of  $\Delta'$  with  $|L| \leq e-1$ . Since  $R = \Delta' \cap K_n(\Gamma)$  contains exactly  $r$  vertices and each of these is incident with at least  $(e-1)(r-1)/r+1$  differently coloured edges, there is at least an  $\ell \in L$  such that each vertex of  $R$  is incident with an edge of colour  $\ell$ . Thus, the set

$$C_\ell = \{e \in E' : w(e) = \ell\}$$

is a full matching for  $\Delta'$ . Now, for any  $r \in R$ , define  $\xi(r) = s$ , where  $(r, s) \in C_\ell$ . This completes the proof.  $\square$

**Example 4.7.** An interesting case for Theorem 4.6 occurs when  $d$  is taken to be as large as possible, namely  $d = e-1$ . Since, in this case, by (2) and (4)

$$r = \frac{1}{e}|K_n(\Gamma)|,$$

Condition (3) is always satisfied. We provide now an actual example where this happens. Suppose  $n$  to be even and let  $\Gamma = K_{n/2}$  and  $\Gamma' = K_{n/2-1}$ . Each element of  $K_n(\Gamma')$  is contained in  $e = n/2+1$  elements of  $K_n(\Gamma)$ , while  $\Gamma$  contains  $d = n/2$  elements of  $K_n(\Gamma')$ .

## 5 Examples and applications

As said above, in this section we will show direct constructions of samplings for some complete designs. A convenient approach is to consider a suitable automorphism group of the designs which is also compatible with the sampling we wish to find, in the sense of the following definition.

**Definition 5.1.** Let  $\mathfrak{B}$  be a  $(K_n, \Gamma)$ -design and let  $\mathfrak{B}'$  be a  $(K_n, \Gamma')$ -design, with  $\Gamma' \leq \Gamma$ , and suppose  $\xi : \mathfrak{B} \rightarrow \mathfrak{B}'$  to be a sampling. An *automorphism*  $\alpha$  of  $\xi$  is an automorphism of  $\mathfrak{B}'$  and  $\mathfrak{B}$  such that for any  $B \in \mathfrak{B}$ ,

$$\xi(\alpha(B)) = \alpha(\xi(B)).$$

Observe that an analogous definition is possible also for embeddings; see, for instance [5, Theorem 3.2] where a  $2 - (p, 3, 1)$  design is cyclically embedded into a cyclic  $2 - (4p, 4, 1)$  design.

Let  $n$  be an integer. From now on, we shall mean by  $\mathbb{Z}_n^\square$  the group of all the invertible elements in  $\mathbb{Z}_n$  which are squares.

**Example 5.2.** Fix  $n$ . Let  $\Gamma = C_k \leq K_n$  be a cycle on  $k$  vertices, and write  $\Gamma' = P_h \leq C_k$  for a path of length  $h$  in  $C_k$ . We have

$$|K_n(C_k)| = \binom{n}{k} \frac{(k-1)!}{2}; \quad |K_n(P_h)| = \binom{n}{h} \frac{h!}{2}.$$

By Theorem 4.3,  $K_n(C_k)$  admits a regular  $P_h$ -sampling, if, and only if,

$$\lambda = \frac{|K_n(C_k)|}{|K_n(P_h)|} = \frac{(n-h)!}{(n-k)!k} \in \mathbb{N}.$$

In general, even with the existence of a group action compatible with the structures involved, it is not easy to actually determine a sampling.

We write a full example just for  $n = 7$ ,  $k = 4$  and  $h = 3$ ; here,  $\lambda = 1$ . Identify the vertices of  $K_7$  with the elements of  $\mathbb{Z}_7$ . First, we wish to find a group  $G$  which is

1. transitive on  $K_7$ ;
2. acts in a semiregular way on  $K_7(C_4)$  and, possibly, on  $K_7(P_3)$ .

Such a group  $G$ , if it exists, it is necessarily isomorphic to  $H/\text{Stab}_H(C)$  for some  $H \leq S_7$  and any  $C \in K_7(C_4)$ . Thus, we need first to determine all  $H \leq S_7$  normalising at least  $\text{Stab}_H(C_4)$ . A direct computation shows that, up to conjugacy, there are just two classes of such subgroups:

- (a) one consisting of cyclic groups of order 7 isomorphic to  $(\mathbb{Z}_7, +)$ ,
- (b) the other containing groups of order 21 isomorphic to  $G = \mathbb{Z}_7^\square \rtimes \mathbb{Z}_7$ , where, for  $(\alpha, \beta), (\alpha', \beta') \in G$ ,

$$(\alpha, \beta)(\alpha', \beta') = (\alpha\alpha', \beta + \alpha\beta').$$

The action of  $G$  on  $V(K_7) = \mathbb{Z}_7$  is given by

$$(\alpha, \beta)(x) = \alpha x + \beta.$$

It might be checked that the action induced by both these groups on  $K_7(C_4)$  and  $K_7(P_3)$  is semiregular.

We now describe 2 different  $\xi$ -samplings.

First consider the group  $(\mathbb{Z}_7, +)$ . In this case, a complete system of representatives for  $K_7(P_3)$  is given by the paths

$$\begin{array}{ccccccccc} 012 & 013 & 014 & 015 & 016 & 023 & 024 & 025 & 026 & 034 \\ 035 & 036 & 045 & 046 & 056 & & & & & \end{array}$$

Recall that two triples  $abc$  and  $def$  represent the same path in  $K_7(P_3)$  if, and only if, either  $abc = def$  or  $abc = fed$ . Suitable representatives for the orbits of  $K_7(C_4)$  turn out to be

$$\begin{array}{ccccc} \underline{0126} & \underline{0136} & \underline{0146} & \underline{0152} & \underline{0163} \\ \underline{0231} & \underline{0245} & \underline{0253} & \underline{0261} & \underline{0346} \\ \underline{0351} & \underline{0362} & \underline{0451} & \underline{0461} & \underline{0562} \end{array}$$

The subpath selected by the sampling  $\widehat{\xi}$  is given, for each representative, by the underlined elements, which have to be taken in the order they actually appear. As above, observe that the elements of  $K_7(C_4)$  are not sets; in particular, two quadruples  $abcd$  and  $a'b'c'd'$  represent the same graph if, and only if, they belong to the same orbit of  $\mathbb{Z}_7^4$  under the action of  $D_8$ , the dihedral group of order 8.

If the group  $\mathbb{Z}_7^{\square} \times \mathbb{Z}_7$  is chosen for the construction, then a complete system of representatives for  $K_7(P_3)$  is just

$$012 \quad 013 \quad 014 \quad 015 \quad 035.$$

A related system of representatives for  $K_7(C_4)$  is determined as

$$\underline{0126} \quad \underline{0136} \quad \underline{0146} \quad \underline{0154} \quad \underline{0351}.$$

The image of 0126, 0136, 0146 and 0351 in the sampling  $\zeta$  induced by these representatives is the same as that in the sampling  $\xi$  described above; however, it is not possible to choose  $\zeta(0152) = 015$  again, since 0152 now belongs to the orbit of 0146; thus, its sample is uniquely determined by  $\zeta(0146) = 014$  and it must be  $\zeta(0152) = 025$ . This shows that  $G$  is an automorphism group of  $\zeta$ , but not of  $\xi$ .

If we take both the graphs  $\Gamma$  and  $\Gamma'$  to be complete, we may apply Theorem 4.3 to the study of embeddings and samplings of complete designs in the classical sense.

We remark that the problem of determining a regular  $K_1$ -sampling with redundancy 1 of  $K_n(K_k)$  is exactly that of determining a system of distinct representatives for the  $k$ -sets of a set of cardinality  $n$ ; see [12, 13].

For any finite set  $S$  of cardinality  $n$ , denote by  $\binom{S}{k}$  the set of all subsets of  $S$  with  $k$  elements.

**Corollary 5.3.** *There exists a regular  $k'$ -sampling*

$$\xi : \binom{S}{k} \rightarrow \binom{S}{k'}$$

*if, and only if, there is  $\lambda \in \mathbb{N}$  such that*

$$\binom{n}{k} = \lambda \binom{n}{k'}.$$

*The redundancy of this sampling is  $\lambda$ .*

**Corollary 5.4.** *Let  $S$  be a finite set with  $|S| = n$ . Suppose  $k \leq \lfloor n/2 \rfloor$ . Then, there exist a bijective sampling*

$$\xi : \binom{S}{n-k} \rightarrow \binom{S}{k}.$$

**Remark 5.5.** Corollary 5.3 guarantees the existence of a regular  $k'$ -sampling of  $\binom{S}{k}$  with redundancy  $\lambda$  every time the necessary condition

$$\binom{n}{k} = \lambda \binom{n}{k'}$$

holds; yet our proof is non-constructive.

In at least some cases, however, it might possible to write at least some sampling functions  $\xi$  in a more direct way.

The main idea, as before, is to describe both  $\binom{S}{k}$  and  $\binom{S}{k'}$  as union of orbits under the action of a suitable group  $G$ , acting on  $S$ , and determine systems of representatives  $T$  and  $U$  such that:

1.  $T \subseteq \binom{S}{k}$ ,  $U \subseteq \binom{S}{k'}$ ;
2.  $G$  is semiregular on  $\binom{S}{k}$ ;
3. any element of  $u \in U$  is a sample of  $\lambda/|\text{Stab}_G(u)|$  elements of  $T$  and
4. for any  $\sigma \in G$  and  $t \in T$ ,

$$\sigma(\xi(t)) = \xi(\sigma(t)).$$

**Example 5.6.** Suppose  $k = 3$ . We are looking for a regular 2-sampling of  $\binom{S}{3}$ ; thus,  $\lambda = (n-2)/3$ . By Corollary 5.3 such a regular 2-sampling  $\xi$  exists if, and only if,  $n \equiv 2 \pmod{3}$ . Observe that when  $n$  is even,  $\lambda$  is also even.

In order to explicitly find  $\xi$ , consider the natural action of the cyclic group  $(\mathbb{Z}_n, +)$  on the set  $S = \{0, 1, \dots, n-1\}$ : for any  $\eta \in \mathbb{Z}_n$  and  $s \in S$ , let

$$\eta(s) = s + \eta \pmod{n}.$$

Fix  $v = \lfloor n/2 \rfloor$ . It is easy to show that a complete system of representatives for the orbits of  $\mathbb{Z}_n$  on  $\binom{S}{3}$  is given by either  $T = T_1 \cup T_2 \cup T_3 \cup T_4^1$  for  $n$  odd, or  $T = T_1 \cup T_2 \cup T_3 \cup T_4^2$  for  $n$  even, where

$$\begin{aligned}
T_1 &= \{\{0, i, i+t\} \mid i = 1, \dots, \lambda+1; t = 1, \dots, \lambda\} \\
T_2 &= \{\{0, j, u\} \mid j = \lambda+2, \dots, v-1; u = 1, \dots, j-\lambda-1\} \\
T_3 &= \{\{0, \ell, m\} \mid \ell = \lambda+2, \dots, v-1; m = \ell+1, \dots, 2\lambda+1\} \\
T_4^1 &= \{\{0, v, u\} \mid u = 1, \dots, v-\lambda-1, v+1, \dots, 2\lambda+1\} \\
T_4^2 &= \{\{0, v, p\} \mid p = 1, \dots, \lambda/2\}.
\end{aligned} \tag{5}$$

A set of representatives for the orbits of  $\mathbb{Z}_n$  on  $\binom{S}{2}$  is just  $U = \{\{0, x\} : 1 \leq x \leq v\}$ . All orbits of  $\mathbb{Z}_n$  on  $\binom{S}{3}$  have length  $n$ ; thus  $\mathbb{Z}_n$  acts semiregularly on  $\binom{S}{3}$ . When  $n$  is odd, it is also true that  $\text{Stab}_{\mathbb{Z}_n}(y) = \{0\}$  for any  $y \in U$ . However, when  $n$  is even,  $\text{Stab}_{\mathbb{Z}_n}(y) = \{0\}$  for  $y \neq \{0, v\}$  but  $\text{Stab}_{\mathbb{Z}_n}(y) = \{0, v\}$  when  $y = \{0, v\}$ . We now introduce a function  $\widehat{\xi} : T \rightarrow U$  such that each  $y \in U$ ,  $y \neq \{0, v\}$  has  $\lambda$  preimages in  $T$ , while  $\{0, v\}$  for  $v$  even has  $\lambda/2$  preimages. Indeed, for each element  $\{0, \ell, m\}$  in  $T_i$ , where  $\ell$  and  $m$  are to be taken in the same order as they appear in (5), let

$$\widehat{\xi}(\{0, \ell, m\}) = \{0, \ell\}.$$

Since  $\mathbb{Z}_n$  is semiregular on  $\binom{S}{3}$  and  $T$  is a set of representatives for its orbits, for any  $\{a, b, c\} \in \binom{S}{3}$  there is exactly one  $\eta \in \mathbb{Z}_n$  and  $\{0, \ell, m\} \in T$  such that  $\eta(\{0, \ell, m\}) = \{a, b, c\}$ . Thus, the definition

$$\xi(\{a, b, c\}) = \xi(\eta(\{0, \ell, m\})) = \eta(\widehat{\xi}(\{0, \ell, m\})) = \eta(\{0, \ell\}) = \{\eta, \ell + \eta\}$$

is well posed. We claim that  $\xi$  is a regular 2-sampling of  $\binom{S}{3}$ . Since for any  $\{s, t\} \in \binom{S}{2}$  there exists  $\eta \in \mathbb{Z}_n$  such that  $\{s, t\} = \eta(\{0, \ell\})$ , in order to show that  $\xi$  is a sampling we just need to prove that the number of preimages in  $\binom{S}{3}$  of  $\{0, \ell\}$  under  $\widehat{\xi}$  is exactly  $\lambda$ . Observe that for  $n$  odd or  $\ell \neq v$ , the only preimages of  $\{0, \ell\}$  are elements of  $T$ ; thus, we have to analyse the following cases:

1. for  $1 < \ell \leq \lambda+1$ , the set  $\{0, \ell\}$  has  $\lambda$  preimages in the class  $T_1$  and none in  $T_2, T_3, T_4^1$  or  $T_4^2$  and we are done;
2. for  $\lambda+2 \leq \ell < v$ , the set  $\{0, \ell\}$  has  $\ell - \lambda - 1$  preimages in  $T_2$  and  $2\lambda + 1 - \ell$  preimages in  $T_3$ , for a total of  $\lambda$ ;
3. if  $\ell = v$  and  $n$  is odd, then  $\{0, \ell\}$  has  $\lambda$  preimages in  $T_4^1$ .

In  $n$  is even and  $\ell = v$ , then each orbit of an element of  $T_4^2$  contains two preimages of  $\{0, v\}$ ; since  $|T_4^2| = \lambda/2$ , we get that also in this case the total number of preimages is  $\lambda$ . It follows that  $\xi$  is, as requested, a regular 2-sampling for  $\binom{S}{3}$ .

We now show how this construction might be used for some small cases:

1. for  $n = 14$  we have  $\lambda = 4$ ,  $v = 7$ . The set  $T$  is as follows:

$$\begin{array}{l} T_1: \underline{012} \quad \underline{013} \quad \underline{014} \quad \underline{015} \quad \underline{023} \quad \underline{024} \quad \underline{025} \quad \underline{026} \quad \underline{034} \quad \underline{035} \\ \quad \underline{036} \quad \underline{037} \quad \underline{045} \quad \underline{046} \quad \underline{047} \quad \underline{048} \quad \underline{056} \quad \underline{057} \quad \underline{058} \quad \underline{059} \\ T_2: \underline{067} \quad \underline{068} \quad \underline{069} \\ T_3: \underline{061} \\ T_4^2: \underline{071} \quad \underline{072} \end{array}$$

The underlined elements in the preceding table are the image under  $\widehat{\xi}$  of the corresponding set.

2. for  $n = 17$  we have  $\lambda = 5$ ,  $v = 8$ . We describe  $T$  and  $\widehat{\xi}$  as before. In the following table, by  $a$  and  $b$  we respectively mean 10 and 11.

$$\begin{array}{l} T_1: \underline{012} \quad \underline{013} \quad \underline{014} \quad \underline{015} \quad \underline{016} \quad \underline{023} \quad \underline{024} \quad \underline{025} \quad \underline{026} \quad \underline{027} \\ \quad \underline{034} \quad \underline{035} \quad \underline{036} \quad \underline{037} \quad \underline{038} \quad \underline{045} \quad \underline{046} \quad \underline{047} \quad \underline{048} \quad \underline{049} \\ \quad \underline{056} \quad \underline{057} \quad \underline{058} \quad \underline{059} \quad \underline{05a} \quad \underline{067} \quad \underline{068} \quad \underline{069} \quad \underline{06a} \quad \underline{06b} \\ T_2: \underline{078} \quad \underline{079} \quad \underline{07a} \quad \underline{07b} \\ T_3: \underline{071} \\ T_4^1: \underline{081} \quad \underline{082} \quad \underline{089} \quad \underline{08a} \quad \underline{08b} \end{array}$$

**Example 5.7.** We wish to determine a regular 3-sampling  $\xi$  of  $\binom{S}{4}$ . In this case,  $k = 4$ ,  $\lambda = 5$ . To construct  $\xi$  it is convenient to describe  $\binom{S}{4}$  as union of orbits of a fairly large semiregular group. We may consider, as in Example 5.2, the group

$$G = \mathbb{Z}_n^\square \times \mathbb{Z}_n.$$

For  $n$  a prime with  $n \equiv 11 \pmod{12}$ , simple, but tedious, computations show that the action of  $G$  is semiregular on both  $\binom{S}{3}$  and  $\binom{S}{4}$ . The smallest interesting case occurs for  $n = 23$ . Here, a system of representatives for the orbits of  $\binom{S}{3}$  is

$$U = \{ 0, 1, 2 \quad 0, 1, 3 \quad 0, 1, 4 \quad 0, 1, 5 \quad 0, 1, 7 \quad 0, 1, 9 \quad 0, 1, 13 \}.$$

By a computer assisted search with [8], we determined the following system compatible with  $U$  of representatives for the orbits of  $\binom{S}{4}$ :

$$\begin{array}{l} \underline{0,1,2,5} \quad \underline{0,1,2,7} \quad \underline{0,1,2,10} \quad \underline{0,1,2,11} \quad \underline{0,1,2,14} \\ \underline{0,1,3,7} \quad \underline{0,1,3,15} \quad \underline{0,1,3,19} \quad \underline{0,1,3,21} \quad \underline{0,1,3,22} \\ \underline{0,1,4,5} \quad \underline{0,1,4,7} \quad \underline{0,1,4,11} \quad \underline{0,1,4,15} \quad \underline{0,1,4,17} \\ \underline{0,1,5,6} \quad \underline{0,1,5,14} \quad \underline{0,1,5,15} \quad \underline{0,1,5,20} \quad \underline{0,1,5,22} \\ \underline{0,1,7,5} \quad \underline{0,1,7,9} \quad \underline{0,1,7,10} \quad \underline{0,1,7,21} \quad \underline{0,1,7,22} \\ \underline{0,1,9,2} \quad \underline{0,1,9,5} \quad \underline{0,1,9,8} \quad \underline{0,1,9,16} \quad \underline{0,1,9,20} \\ \underline{0,1,13,3} \quad \underline{0,1,13,5} \quad \underline{0,1,13,7} \quad \underline{0,1,13,9} \quad \underline{0,1,13,12}. \end{array}$$

The sampling map  $\widehat{\xi}$  is defined as in the previous example.

We remark that, instead of the group  $G$ , we might also have considered the action of the cyclic group  $\mathbb{Z}_{23}$ , as in Example 5.2. However, had this been the case, we would have needed to write 77 distinct representatives for the orbits of  $\binom{S}{3}$  and 385 compatible representatives for the orbits of  $\binom{S}{4}$ .

**Remark 5.8.** If  $\binom{S}{k}$  admits a regular  $k_1$ -sampling  $\xi_1$  with redundancy  $\lambda_1$  and  $\binom{S}{k_1}$  admits, in turn, a regular  $k_2$ -sampling  $\xi_2$  with redundancy  $\lambda_2$ , then  $\xi = \xi_2\xi_1$  is a regular  $k_2$ -sampling of  $\binom{S}{k}$  with redundancy  $\lambda_1\lambda_2$ , since any  $x_2 \in \binom{S}{k_2}$  is a sample of  $\lambda_2$  elements of  $\binom{S}{k_1}$ , while, on the other hand, any  $x_1 \in \binom{S}{k_1}$  is a sample of  $\lambda_1$  elements of  $\binom{S}{k}$ . However, it has to be stressed that not all  $k_2$ -samplings of  $\binom{S}{k}$  arise in this way.

**Example 5.9.** For  $n = 11$ , the necessary condition for the existence of a regular 2-sampling of  $\binom{S}{3}$  as well as that for the existence of a regular 3-sampling of  $\binom{S}{4}$  are simultaneously fulfilled. In particular, it is possible to construct a regular 2-sampling  $\xi$  to  $\binom{S}{4}$  with redundancy  $\lambda = 6$  as composition of a regular 2-sampling  $\xi_1$  of  $\binom{S}{3}$  and a regular 3-sampling  $\xi_2$  of  $\binom{S}{4}$ . We consider the action of the group  $G$  introduced in Example 5.7. As before,  $G$  is semiregular on  $\binom{S}{4}$  and  $\binom{S}{3}$ . Furthermore, a direct computation shows that  $G$  is regular on  $\binom{S}{2}$ . We provide suitable systems of representatives:

$$\begin{aligned} U_2: & 01 \\ U_3: & \underline{012} \quad \underline{013} \quad \underline{015} \\ T : & \underline{0123} \quad \underline{0124} \quad \underline{0135} \quad \underline{0137} \quad \underline{0154} \quad \underline{0158} \end{aligned}$$

The samplings arise, as in the previous examples, from  $\widehat{\xi}_1 : U_3 \rightarrow U_2$  and  $\widehat{\xi}_2 : T \rightarrow U_3$ . It is immediate to see that  $\widehat{\xi} = \widehat{\xi}_1\widehat{\xi}_2$  is a regular 2-sampling of  $\binom{S}{4}$ . On the other hand, it is possible to define a regular 2-sampling of  $\binom{S}{4}$  also from the starter set

$$T: \underline{0123} \quad \underline{0124} \quad \underline{0125} \quad \underline{0126} \quad \underline{0128} \quad \underline{0134} \quad .$$

However, it is not possible to extract a regular 3-sampling (with redundancy 2) from  $T$ .

The notion of  $(K_n, \Gamma)$ -complete design can be further generalized to that of a  $(\Delta, \Gamma)$ -complete design, where  $\Delta$  is an arbitrary graph. As before, given  $\Gamma' \leq \Gamma \leq \Delta$ , we might want to investigate the existence of a regular  $\Gamma'$ -sampling of  $\Delta(\Gamma)$  or, conversely, an embedding of  $\Delta(\Gamma')$  into  $\Delta(\Gamma)$ . However, in this general case, Lemma 4.1 fails, since it is not possible to guarantee that  $\text{Aut}(\Delta)$  acts transitively on the blocks of  $\Delta(\Gamma)$  and  $\Delta(\Gamma')$ ; hence it is not possible to get an analogue of Theorem 4.3. The following example contains a case in which a sampling might be shown to exist (and at least one of these samplings can be determined in an independent way).

**Example 5.10.** Let  $q$  be any prime power, and consider the projective space  $PG(3, q)$ . Call  $\widehat{\Delta}$  the bipartite point-line incidence graph of this geometry. Let  $\widehat{\Gamma}$  be the point-line incidence graph of  $PG(2, q)$ , seen as a plane embedded into  $PG(3, q)$ . Clearly  $\widehat{\Gamma} < \widehat{\Delta}$ . Define two new graphs  $\Delta$  and  $\Gamma$  by replacing in  $\widehat{\Delta}$  and  $\widehat{\Gamma}$  each vertex  $v$  corresponding to a point of  $PG(3, q)$  with a triangle  $vv'v''$ . Let  $\Gamma'$  be a triangle  $C_3$ . We observe that  $\Delta(\Gamma')$  corresponds to the set of the

points of  $PG(3, q)$ . Since there are as many points in  $PG(3, q)$  as planes, we have  $|\Delta(\Gamma')| = |\Delta(\Gamma)|$ . Furthermore, the full automorphism group of  $\Delta$  contains a subgroup isomorphic to  $PGL(3, q)$ , which acts in a transitive way on  $\Delta(\Gamma)$  and also  $\Delta(\Gamma')$ . Thus, we may apply the same techniques as in the proof of Lemma 4.1, as to obtain a regular matching of  $\Delta$ , as in Theorem 4.3. This gives a sampling that associates to every plane  $\pi$  of  $PG(3, q)$  a point  $p \in \pi$ .

There are several possible matchings of this kind; one of these is given by the action of a symplectic polarity  $\sigma$  of  $PG(3, q)$ .

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